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Suitability of pesticide risk indicators for less developed countries: a comparison

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Abstract

Pesticide risk indicators provide simple support in the assessment of environmental and health risks from pesticide use, and can therefore inform policies to foster a sustainable interaction of agriculture with the environment. For their relative simplicity, indicators may be particularly useful under conditions of limited data availability and resources, such as in Less Developed Countries (LDC). However, indicator complexity can vary significantly, in particular between those that rely on an exposure-toxicity ratio (ETR) and those that do not. In addition, pesticide risk indicators are usually developed for Western contexts, which might cause incorrect estimation in LDCs. This study investigated the appropriateness of seven pesticide risk indicators for use in LDCs, with reference to smallholding agriculture in Colombia. Seven farm-level indicators, among which 3 relied on an ETR (POCER, EPRIP, PIRI) and 4 on a non-ETR approach (EIQ, PestScreen, OHRI, Dosemeci et al., 2002), were calculated and then compared by means of the Spearman rank correlation test. Indicators were also compared with respect to key indicator characteristics, i.e. user friendliness and ability to represent the system under study. The comparison of the indicators in terms of the total environmental risk

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suggests that the indicators not relying on an ETR approach cannot be used as a reliable proxy for more complex, i.e. ETR, indicators. ETR indicators, when user-friendly, show a comparative advantage over non-ETR in best combining the need for a relatively simple tool to be used in contexts of limited data availability and resources, and for a reliable estimation of environmental risk. Non-ETR indicators remain useful and accessible tools to discriminate between different pesticides prior to application. Concerning the human health risk, simple algorithms seem more appropriate for assessing human health risk in LDCs. However, further research on health risk indicators and their validation under LDC conditions is needed.

Keywords

Pesticide use, environmental risk, occupational health risk, assessment, indicator, Colombia

1. Introduction

Pesticide risk indicators can support the assessment of environmental and health risks from pesticide use. They can be utilized by different kinds of users, such as farmers, extension agents, policy-makers, regulatory agencies and academia (Levitan, 2000). They serve as a basis for the evaluation of different pest management strategies (Levitan, 2000; Greitens and Day, 2007), and for the development, monitoring and assessment of environmental and health policies (Levitan, 2000; Maud et al., 2001; Falconer, 2002; Finizio and Villa, 2002). Thus, pesticide risk indicators can signal risky agricultural practices and inform interventions and policies to foster a sustainable interaction of agriculture with the environment on which agriculture itself relies. The contribution of pesticide risk indicators, and more in general of sustainability indicators, in helping minimising the impact of agriculture on the environment has been recognized not only in academia, but in the policy arena, which has often taken a proactive role in stimulating research on sustainability indicators in agriculture (e.g. CEC, 1999; OECD 1999 and 2001).

Simplicity is a generally acknowledged feature of indicators. This often makes them acceptable, usable even with scarce data, quick to calculate and easy to communicate, although at the expense of a more realistic representation of pesticide impacts (van der Werf, 1996; Castoldi et al., 2007). In this regard, indicator-based assessment methods gain a comparative advantage over alternative assessment systems, such as direct measurements or simulation modelling, which instead require more qualified expertise, economic resources and data which might not always be available.

However, the level of complexity of pesticide risk indicators can also vary significantly. Two broad typologies of indicators can be identified (Reus et al., 2002). The first includes user friendly assessment tools, usually with few input data requirements, and a scoring table based on rather simple algorithms which are often constructed on the basis of expert judgment. These indicators usually score pesticide properties first, which are then multiplied by the application rate. Finally, the scores are aggregated by summation. The second typology includes indicators using a risk-ratio, or exposure-toxicity ratio (ETR) approach, i.e. “the ratio between exposure (usually the concentration in a certain environmental compartment) and toxicity for relevant organisms” (Reus et al., 2002). These indicators are considered to better represent and quantify environmental risks from pesticide use, but have the drawbacks of requiring more detailed input data and the support of computer modelling (Reus et al., 2002; Castoldi et al., 2007). These indicators use the application rate to calculate pesticide concentrations, which are then scored by environmental compartment. The compartment scores can then be integrated by summation or by multiplication. Thus, from a mathematical perspective, the most significant difference between ETR and non-ETR indicators is how the application rate is included in the risk estimation.

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The extent to which simple and complex pesticide risk indicators provide convergent assessment results is an open issue. Convergent results would allow for considering simple indicators as proxy to the more complex ones, and therefore allow them to be used as easy-to-use diagnostic tools. However, previous comparative studies highlighted a divergence rather than a convergence in assessment results (e.g. Maud et al., 2001; Reus et al., 2002).

The quest for simple but reliable assessment methods is particularly relevant in Less Developed Countries (LDC). In effect, not only are LDCs often characterised by particularly serious pesticide-related externalities (e.g. Pimentel et al., 1992; Ecobichon, 2001), but also by a general limited ability in environmental and agricultural research and monitoring. The latter can be in broad terms related to two issues, i.e. lack of skilled human resources, with brain drain and de-qualification affecting many countries (UNESCO, 2009), and lack of infrastructure (e.g. information technology, laboratories) and financial resources to access and produce reliable data and information (Zhen and Routray, 2003; UNESCO, 2009).

Furthermore, one open issue is that pesticide risk indicators are usually developed for productive and pedoclimatic conditions in Western countries, which might imply, especially for indicators relying on expert judgement, an incorrect assessment of pesticide risks in LDCs. Pesticide risk indicators have been used in LDCs, but usually with a preference for simple, non-ETR types (e.g. Muhammetoglu and Uslu, 2007; Pradel et al., 2009), an exception being a study of Kookana et al. (2007). However, while comparative evaluations of pesticide risk indicators exist (e.g. Maud et al., 2001; Reus et al., 2002; Stenrod et al., 2008), they do not refer to the conditions of resource availability usually encountered in LDCs. Moreover, comparative evaluations of indicators have neglected human health risk indicators. Analysing also this kind of indicators is of fundamental importance in LDCs, because pesticide application practices often differ significantly from those adopted in Western countries (Matthews, 2008). Such differences in contextual factors, in particular pesticide application techniques, suggest that the applicability of health risk indicators in LDCs might be limited, and call for the need for contextualizing pesticide risk, e.g. to understand the determinants of exposure more than to quantify levels of risk (Blanco et al., 2005).

Consequently, it is not clear what indicators might be more appropriate to assess environmental and health risks from pesticide use, and thus properly inform agricultural management, under pesticide application practices typical of LDCs. The objective of this study was to investigate the appropriateness of seven pesticide risk indicators for use at farm level in LDCs, with particular reference to smallholding agriculture in the Colombian Andean region. With reference to this area, two research questions drove the study:

i) Can simple pesticide risk indicators be used as proxies for more complex ones, thus facilitating the task of risk assessment?

ii) What is the most appropriate indicator to assess pesticide risk to human health and the environment?

The paper is structured as follows. Firstly, a short description of the indicators selected, study area, data used and comparative procedure adopted are provided. Secondly, the results are presented separately for environmental and human health risk indicators. Finally, results are discussed with reference to the two research questions, and conclusions on the use of pesticide risk indicators in the context of LDCs are drawn.

2. Method

2.1. Indicators

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Seven farm-level indicators (i.e. EIQ, PestScreen, EPRIP, PIRI, POCER, OHRI and the indicator proposed by Dosemeci et al., 2002) were selected so that i) every environmental and health compartment was considered by at least two of the selected indicators and ii) both simple, i.e. non-ETR, and complex, i.e. ETR, indicators were represented (Table 1).

2.1.1. Coverage of environmental and health compartments

Three indicators, i.e. PestScreen (Juraske et al., 2007), EPRIP (Padovani et al., 2004; Trevisan et al., 2009), and PIRI (Kookana et al., 2005), focus exclusively on environmental risks, whereby risk to consumer health is implicitly and partly included, since drinking water contamination and ingestion of contaminated food are part of the environmental risk assessment. Two indicators, i.e. OHRI (Bergkvist, 2004) and the indicator developed by Dosemeci et al. (2002), focus solely on occupational health risk, whereby only the pesticide operator is considered. The remaining two indicators, i.e. EIQ (Kovach et al., 1992) and POCER (Vercruysse and Steurbaut, 2002), include an environmental risk component and an occupational health risk component, whereby both assess the risk to agricultural workers in addition to pesticide operators and POCER also considers bystanders' risk to pesticide exposure (a short description of the indicators is given in the supplementary data files).

2.1.2. Representation of ETR and non-ETR indicators

Four indicators were chosen that do not rely on an ETR approach, i.e. they transform variables into scores which, in turn, are aggregated empirically (EIQ, PestScreen, OHRI and the indicator from Dosemeci et al., 2002), and three indicators were chosen which rely on the ETR approach (POCER, EPRIP, PIRI). The first four indicators are considered simple indicators because they do not make use of site specific data (e.g. pedoclimatic conditions) and because pre-calculated hazard scores are multiplied with application rates by the end-user, which results in low data requirements. The latter three indicators take into account site specific data, make use of the ETR approach and are more data demanding.

2.1.3. Further indicator characteristics

PestScreen, POCER, EPRIP and PIRI all implement at least some of the suggestions made in earlier studies for the development of more accurate pesticide risk indicators (Levitan, 1997 and 2000; Maud et al., 2001; Reus et al., 2002). Among these suggestions were: to be analogous to the technical concept of risk, to have large potential ranges to allow for differentiation between pesticides, to include application rate, application factors and environmental conditions, to give separate rankings for different compartments (including human health). On the other hand, EIQ is one of the most dated, but also one of the most widely used indicators, with numerous applications in LDCs (e.g. Muhammetoglu and Uslu, 2007; Pradel et al., 2009).

Finally, all indicators chosen present a relative outcome. That is, instead of providing an absolute value, the assessment provides a qualitative statement on the relative risks a pesticide application or control strategy might have in comparison to the application of another pesticide or to a control strategy based on different pesticides.

Table 1. Risk indicators considered in this study by environmental and health compartments

	Environment					Health			Calculation methodology	
Indicator	Soil	Air	Surface water	Groundwater	Beneficial arthropods	Pesticide operator	Farm worker	Consumer	ETR	Non-ETR
EIQ			*	*	*	*	*	*		*
PestScreen	*	*	*	*				*		*
POCER	*		*	*	*	*	*	*	*	
EPRIP	*	*	*	*				*	*	
PIRI			*	*				*	*	
OHRI						*				*
Dosemeci et al. (2002)						*				*

2.2. Data

2.2.1. Data and study area

The data necessary to calculate the indicator rankings were mainly derived from an existing georeferenced dataset produced in a previous study in the *vereda* (community) called La Hoya, located in the Department of Boyacá, in the eastern chain of the Colombian Andes (Feola, 2010a). For many aspects such as pesticide application technique or socio-demographic structure, this study area may be considered typical of the broader Andean region (Feola, 2010a) and very similar to other rural areas in LDCs (Matthews, 2008).

Vereda La Hoya ranges from 2,700 to 3,250 masl over an area of 8.4 km^2 (840 ha), and has a population of about 750 inhabitants. It is a rural region mainly dedicated to the cultivation of potato (MADR, 2006). The production of potato in Vereda La Hoya relies mainly on smallholders, who cultivate an average of 3 hectares subdivided into different plots. The land is cultivated in two cycles a year (September to February and March to August). Average productivity rates range between 15 and 17 ton/ha (MADR, 2006). Potato crops in this region are vulnerable to three major pests: the soil-dwelling larvae of the Andean weevil (*Premnotrypes vorax*), the late blight fungus (*Phytophthora infestans*) and the Guatemalan potato moth (*Tecia solanivora*) . To protect the crop from these pests, the use of chemical pesticides, in particular insecticides and fungicides, is widespread among smallholders (Feola and Binder, 2010b). The most common way of applying pesticide is by means of a lever-operated knapsack sprayer (20-25 litres), which is filled from a bigger tank, usually of about 200 litres, where the pesticide mix is prepared.

Also as a result of the misuse of personal protective equipment (PPE), high levels of pesticide-related health risk have been observed in the region (Cardenas et al., 2005; Ospina et al., 2008; Feola, 2010b). Regarding adverse environmental effects, both Schoell and Binder (2009) and Feola and Binder (2010b) reported that farmers in Vereda La Hoya observed a pesticide-related reduction of soil biodiversity in recent years. Finally, pesticide overuse has attracted the concern of governmental agencies because of its economic drawbacks (MADR, 2004). In this respect, Feola and Binder (2010b), showed that some of the farmers tend to use pesticides ineffectively, with a persistent overuse.

The data used in this study to calculate the indicator values were gathered through a survey carried out in La Hoya in 2007 (Feola and Binder, 2010c). The data consisted of detailed information on 72 farmers' safety practices (e.g. hygiene and use of personal protective equipment) and pesticide applications on one selected plot. The reference period for the data was one entire agricultural cycle (March to August 2007).

2.2.2. Additional data

Additional data necessary to calculate the indicators was gathered from various sources. Pesticide properties were obtained through the Pesticide Properties Database (PPDB, 2009). Climatic data, such as precipitation and temperature (for the years 1994-2003), were obtained from the Instituto de Hidrologia, Meteorologia y Estudios Ambientales de Colombia. For the reference period the temperature was between an average minimum of 5.7 °C and an average maximum of 20 °C. Total annual precipitation in the reference period was 343.5 mm. For soil parameters, the classification of "clay loam" was used (Binder and Patzel, 2001). According to Leuenberger (2005) average organic carbon content in the study area was 6.4%. Mean bulk density was assumed to be 0.9 tons per m^3 according to Binder and Patzel (2001). Soil loss was adapted from Binder and Patzel (2001) and assumed to be 9.6 tons per hectare and year. The distance of the plot to water bodies was calculated with the software ESRI ArcGIS 9.3. An overview of the data used to calculate the indicators is available in the supplementary data files.

2.3. Procedure

The study consisted of three phases. First, the indicator values were calculated for the pest control strategy and for single pesticide applications. A pest control strategy is defined for each of the 72 farmers as the total amount of pesticide applied by active ingredient (examples of pesticide application patterns and strategies can be found in Feola and Binder, 2010b, and Juraske et al., 2011). For EIQ and EPRIP, the number, frequency and sequence of applications also contributes in differentiating among pest control strategies, since they propose how to calculate the cumulative risk which occurs when several applications of different active ingredients are used within the same pest control strategy. Concerning the single pesticide applications, the 72 farmers applied pesticides a total of 1772 times to their fields during the agricultural cycle considered. These applications were aggregated by summing up all applications of a particular pesticide during each of the five production phases (i.e. sowing of the potato, emergence of the shoot, weeding, earthing up, and maintenance). For example, if a farmer applied carbofuran four times with varying application rates during the emergence of the potato shoot, the indicator values were calculated for all four applications taken together. Accordingly, the amount of applications analysed decreased to 581. In sum, 72 pest control strategies, i.e. each strategy consisting of all applications for each single farmer, and 581 pesticide applications, were considered.

Second, the indicator rankings were compared by means of the Spearman rank correlation test, in accordance with Maud et al. (2001) and Reus et al. (2002), and using the software PASW Statistics 18.0. Not only were the indicators compared with respect to their overall outcome (Figure 1, quadrant 1), but also every individual environmental and health risk component that the indicators have in common (Table 1) was compared separately (Figure 1, quadrant 2). Furthermore, the indicators were compared with regard to both the 518 pesticide applications and the 72 control strategies (Figure 1, quadrants 3 and 4). Since only EIQ and EPRIP propose how to calculate the cumulative risk accruing when several applications of different active ingredients are used within the same pest control strategy, the other indicator's values for the pest control strategies were simply summed up from those of the single applications, as proposed by Kovach (1992). Due to the lack of daily meteorological data, the groundwater module of POCER was not calculated through the suggested PESTLA model, but through the groundwater module of the PIRI indicator. PestScreen, which does not propose rankings for single environmental compartments, was compared to other indicators only with respect to the total environmental risk. In addition, the comparison was carried out separately for environmental and occupational health indicators (Figure 1).

Third, a comparison based on key indicator characteristics was made, taking into account each indicator's user friendliness (i.e. data availability, calculation procedure, and interpretation of ranking) and ability to represent the specific system under study (i.e. compartments considered, use of site specific data). The former refers to the procedural dimension of sustainability assessment (Binder et al., 2010), and concerns the indicator best suited to practical use in LDCs. The latter refers to the systemic dimension of sustainability assessment (Binder et al., 2010), and entails the coverage of all relevant ecosystem and human system (i.e. health) compartments. This also entails the use of site specific information, which might significantly alter the estimated level of risk associated with a given application of pesticide due to, for instance, the influence of environmental characteristics such as soil composition on the persistence of active components in the ecosystem under study (the details of the criteria used for this comparison are given in the supplementary data files).

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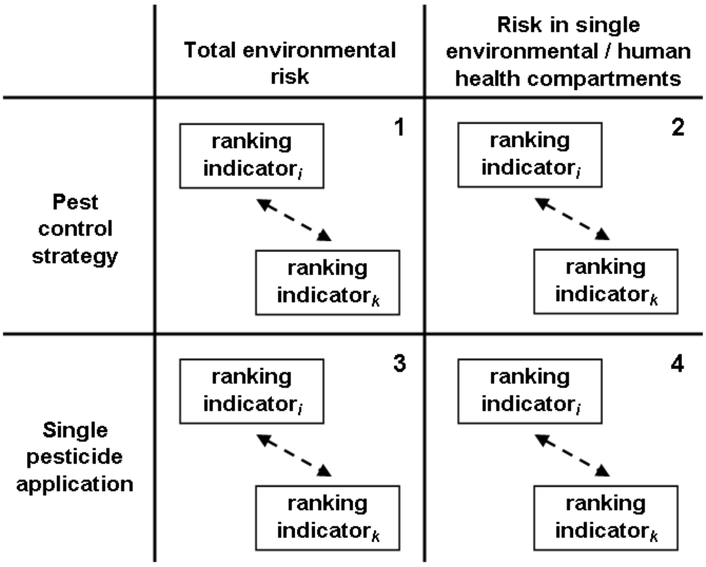

Figure 1. **Comparative analysis of the indicator rankings. The subscripts *i* and *k* indicate indicators among the ones compared in the study.**

3. Results

3.1. Comparison of indicators based on rankings: environmental risk

3.1.1. Total environmental risk

Four indicators aggregate the risk to the different environmental compartments into an overall risk value, namely EIQ, PestScreen, POCER and EPRIP. The highest and significant correlations between rankings were those between EIQ and PestScreen (both non-ETR) and between POCER and EPRIP (both ETR). The latter decreased when control strategy instead of single applications was considered, while all other correlations increased. EIQ and PestScreen showed a high correlation with the application rate (Table 2).

Table 2. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72 control strategies (in *italics*) for total environmental risk (Spearman correlation test)

	EIQ	PestScreen	POCER	EPRIP	Application rate
EIQ	1.00				
PestScreen	0.96 **	1.00			
POCER	-0.08 *	-0.18 **	1.00		
EPRIP	0.12 **	0.02	0.74 **	1.00	
Application rate	0.96 **	0.98 **	-0.27 **	-0.03	1.00

3.1.2. Risk to surface water and groundwater

Four indicators rank the risk to surface water, namely EIQ, POCER, EPRIP and PIRI, while three of these, i.e. EIQ, EPRIP and PIRI, also rank the risk to groundwater. The rankings for all indicators correlated with each other, albeit with differing strength. Regarding the risk to surface water, EPRIP was the only indicator for which the correlation with the other indicators was smaller when the control strategy rather than the single applications was considered, while, for the risk to groundwater, this also occurred for PIRI. EIQ, POCER and PIRI had significant correlations with the application rate. In general, correlations between rankings of the latter (i.e. POCER, EPRIP, PIRI) tended to be higher than those between rankings of ETR and non-ETR indicators (i.e. EIQ) (Tables 3 and 4).

Table 3. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72 control strategies (in *italics*), for risk to surface water (Spearman correlation test)

	EIQ	PestScreen	POCER	EPRIP	Application rate
EIQ	1.00				
PestScreen	0.99 **	1.00			
POCER	0.18	0.18	1.00		
EPRIP	0.05	0.05	0.34 **	1.00	
Application rate	0.98 **	0.98 **	0.12	0.01	1.00

Table 4. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72 control strategies (in *italics*), for risk to groundwater (Spearman correlation test)

	EIQ	POCER	EPRIP	PIRI	Application rate
EIQ	1.00				
POCER	0.45 **	1.00			
EPRIP	0.18 **	0.74 **	1.00		
PIRI	0.40 **	0.64 **	0.43 **	1.00	
Application rate	0.86 **	0.34 **	0.04	0.33 **	1.00

3.1.3. Risk to soil and beneficial arthropods, birds and bees

Two indicators, namely POCER and EPRIP (both ETR), rank the risk to soil. They correlated significantly at 0.01 level (Spearman correlation test 0.82); POCER also correlated significantly with the application rate (Spearman correlation test 0.42).

The risks to beneficial arthropods, birds and bees are each ranked by EIQ and POCER. Significant correlations (at 0.01 level) between the two rankings were observed for the risk to birds, both when single applications and control strategy are considered (Spearman correlation test 0.43 and 0.35 respectively). Regarding the risk to bees, the two rankings correlated significantly (at 0.01 level) only when the control strategy was considered (Spearman correlation test 0.43). Concerning risk to beneficial arthropods, the two rankings were significantly, but negatively, correlated (Spearman correlation test -0.5) when single applications were considered. Finally, for all three compartments, and for both control strategy and single applications, EIQ always correlated significantly at 0.01 level and very strongly (Spearman correlation tests > 0.94) with the application rate (Tables showing the correlations for these three compartments are given in the supplementary data files).

3.2. Comparison of indicators based on rankings: health risk

Four indicators rank the risk to the pesticide operator, namely EIQ, POCER, OHRI and the indicator from Dosemeci et al. (2002). The latter only provides an assessment of the control strategy. When single applications were considered, all rankings correlated with each other significantly (Table 5). Both EIQ and POCER also correlated significantly with the application rate, while OHRI does not include the application rate in its algorithm. However, the rankings correlated less strongly, and in some cases not significantly, when the control strategy was considered (Table 5). The highest correlations were observed between EIQ and POCER, both of which also significantly and strongly correlate with the application rate (Table 5).

Table 5. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72 control strategies (in *italics*), for risk to pesticide operator (Spearman correlation test)

	EIQ	POCER	EPRIP	PIRI	Application rate
EIQ	1.00				
POCER	0.51 **	1.00			
EPRIP	0.13	0.61 **	1.00		
PIRI	0.58 **	0.70 **	0.31 **	1.00	
Application rate	0.94 **	0.38 **	0.30	0.49 **	1.00

Two indicators rank the risk for farm workers, namely EIQ and POCER. The two rankings correlated significantly at the 0.01 level and rather strongly, considering both single applications and control strategies (Spearman correlation tests 0.56 and 0.49 respectively). Both indicators correlated significantly with the application rate (Table given in the supplementary data).

3.3. Comparison of indicators based on key indicator characteristics

The results of the comparison based on key indicator characteristics are shown in Table 6 (the details of the criteria used for this comparison are given in the supplementary data files).

Table 6. Comparison based on key indicator characteristics of the selected indicators.

	EIQ	EPRIP	PIRI	Application rate
EIQ	1.00			
EPRIP	0.10 *	1.00		
PIRI	0.50 **	0.79 **	1.00	
Application rate	0.94 **	-0.08 *	0.34 **	1.00

3.3.1. User friendliness

Data for calculating the majority of the indicators are easily available. Data availability in this analysis does not concern data about the pesticides used by farmers, which are assumed to be available and relatively easy to collect e.g. through a survey, but instead other inputs such as parameters related to their physical and chemical properties, or toxicity.

Data for some pesticides are missing in the indicators' internal databases, and in this study were substituted with the values (for EIQ and PestScreen) or property parameters (for POCER, EPRIP, and PIRI) of pesticide belonging to the same chemical classes. Regarding the health risk component of POCER, the low score in Table 6 depends on the actual, but probably temporary impossibility of accessing the EUROPOEM database, on which this indicator relies. The indicator proposed by Dosemeci et al. (2002) only requires information on pesticide use practices, although rather detailed, and not on pesticide properties.

EIQ and PestScreen can be calculated without a highly specialist knowledge of pesticides and have a simple calculation algorithm. POCER, in particular regarding the groundwater and health modules, needs a higher level understanding of the model used and tends to require a significant amount of time for the calculations.

All indicators except EIQ provide thresholds on which basis pesticide risk classes can be identified, but only EPRIP and PIRI provide such thresholds for both the risk associated with single pesticide applications and for the control strategies. However, PIRI is less transparent than EPRIP on the value at which such thresholds are set.

3.3.2. Ability to represent the system

EIQ and PestScreen do not make use of site specific information, while POCER, EPRIP and PIRI do, thus providing a more appropriate representation of the specific system under analysis. The indicators also differ in terms of environmental compartments considered, and therefore on their ability to produce a comprehensive overview of risk in the environmental system, with PestScreen, POCER and EPRIP covering the most compartments. Concerning health risk, OHRI and the indicator proposed by Dosemeci et al. (2002) are limited to the occupational health of the farm worker.

4. Discussion

4.1. Simple versus complex indicators

Comparison of the indicators with regard to the total environmental risk suggests that simple indicators not relying on an ETR approach cannot be used as a reliable proxy for more complex indicators, i.e. those relying on an ETR approach. In effect, the values of the former (i.e. EIQ, PestScreen) tended to correlate weakly with those of the latter (i.e. EPRIP, POCER and PIRI) when the total environmental risk was considered (Table 2). When single compartments were considered, the correlation between the indicator rankings was stronger, which confirms the results of other studies (Maud et al., 2001; Reus et al., 2002). However, the correlations between non-ETR and ETR indicator values for single compartments were rather weak in the majority of cases (Tables 3 and 4 and supplementary material; Spearman correlation test < 0.6). This confirms the key role played by the calculation method, and in particular by the way the pesticide dose data are mathematically included in the formulas, and by the way compartment scores are aggregated into a total score, in determining the rankings.

Moreover, for both the total environmental risk and the risk in selected compartments, the correlations among all indicators were weaker or not significant when the pest control strategy instead of the single applications was considered (Tables 2 to 4 and supplementary material). This underlines the importance of the aggregation procedure, i.e. from single pesticide applications to pest control strategy, adopted for the different indicators. For EIQ, PestScreen and POCER the individual values of each pesticide applications were summed up. In this procedure, the number of treatments may have a greater impact on the final risk ranking than the impacts of single pesticides, because less and more risky pesticides are equally weighted. At the other extreme, EPRIP is the only indicator among those analysed in this study, which i) gives more weight when high risk occurs in an environmental compartment, ii) relies on a probability function in order to account for a possible cumulative effect of exceeding two thresholds of risk, and iii) accounts for the degradation occurring between single pesticide applications. While some aspects of the aggregation procedure and scoring system are still undergoing validation (Balderacchi and Trevisan, 2010), these are clear strengths of EPRIP in comparison with other indicators.

As also found by Maud et al. (2001), simple indicators tended to be driven by the application rate, which instead was less dominant in determining the values of ETR indicators, since these accord more weight to pesticide properties and environmental conditions such as distance to water body or slope. This difference between the two types of indicators was also tested by calculating ETR indicators using average values for the site specific parameters (not shown in the present paper). This significantly improved the correlations, proving the essential difference marked by using site specific parameters, and also confirmed the good correlation between PestScreen and EPRIP found by Juraske et al. (2007) using constant site specific data for EPRIP.

An additional contribution to the difference in risk rankings between non-ETR and ETR indicators might come from the fact that EIQ and PestScreen adopt low ranges of values, which are likely to distort the differences in risk between pesticides with different properties, as pointed out by other studies (e.g. Dushoff et al., 1994).

Finally, concerning the human health risk the results show a more complex picture, especially when the pest control strategy is considered. Correlations between rankings of different indicators, both ETR and non-ETR, tended to be weak and to change significantly when the control strategies instead of the single applications were considered. These differences were very likely to depend not on the calculation procedure (ETR vs. non-ETR), but on the radically different attribution of risk potential to different factors in the indicators, i.e. misuse of protective equipment and highly toxic pesticides in POCER, powder formulations and large plot areas in OHRI, misuse of personal protective equipment and hygiene habits in Dosemeci et al (2002). Since no other similar comparison of health pesticide risk indicators exists in the literature, it was not possible to compare these results with those of other studies. Further research in this direction is recommended.

4.2. Use of risk indicators in developing countries

LDCs are often characterized by particularly serious pesticide-related externalities but also by a general lack of resources, i.e. data, and expertise dedicated to environmental (Zhen and Routray, 2003; UNESCO, 2009) and health protection (Feola, 2010b), and the promotion of sustainable agricultural production. In this context, the availability of a simple but reliable pesticide risk indicator would be particularly relevant.

With regard to total environmental risk, the result seems to exclude the possibility of using simple, i.e. non-ETR, indicators as proxies for more complex, i.e. ETR, indicators in the assessment of farm-level pesticide-related risk (see also section 4.1). However, recent developments of EPRIP (Trevisan et al., 2009), and in particular the provision of a freely accessible user-friendly software with an internal database, have reduced the complexity of this indicator and made its use relatively simple, even with a data requirement comparable to that of EIQ and PestScreen (Table 6). Moreover, EPRIP is also the indicator that more strictly complies with the other requirements identified by previous studies for the development of more accurate pesticide risk indicators (i.e. Levitan, 1997 and 2000; Maud et al., 2001; Reus et al., 2002). Nevertheless, non-ETR indicators remain very useful and accessible tools for discriminating between different potentially risky pesticides prior to application. In this regard, PestScreen is probably to be preferred to EIQ for it not only includes half life values for single media but makes use of the overall environmental persistence.

Concerning risk in single environmental compartments, the use of single components of different indicators might be considered. For example, PIRI proposes a convincing calculation approach for risk to surface water organisms, with the inclusion of the main transport routes, and accounting for possible site specific mitigation measures, which can be useful for monitoring purposes. The choice of the indicator to be used for a single environmental compartment is likely to depend on the specific research, management or policy needs, on the availability of data and other necessary resources, and on an accurate analysis of the characteristics of the different indicators.

With regard to human health risk indicators, the results do not give strong support for one specific indicator among those analysed. Because uncertainties still exist in the literature on human exposure to pesticide during pesticide application and other operations, it might be preferable to avoid using indicators based on exposure models. In addition, these models are usually developed under European conditions, while it has been shown that in developing countries such as the study area, pesticide application techniques and chemicals used might differ extensively from those conditions (Feola and Binder 2010a and 2010b). In fact, following Blanco et al. (2005), it might be less important to accurately quantify the exposure of farmers to pesticides than to understand the determinants of exposure, both in terms of risk factors (e.g. misuse of personal protective equipment, hygiene habits) and of determinants of risky behaviour (e.g. cost of protective equipment, social norm) (Feola and Binder, 2010a). Consequently, algorithms such as the OHRI or the indicator proposed by Dosemeci et al. (2002) would seem more appropriate in assessing human health risk in developing countries than POCER. They provide a simple algorithm with limited data requirements and can support the identification of the most risky practices in pesticide handling and application. However, these indicators might also suffer from a bias towards North American or European application techniques, since in OHRI parameter values are partly drawn from UKPOEM (UKPOEM, 1992) and in Dosemeci et al. (2002) are mainly drawn from studies in North America and Europe. Further research on the validation of such parameter values in these algorithms under the pesticide application conditions found in many developing countries is needed.

5. Summary of conclusions

This study investigated the appropriateness of seven pesticide risk indicators for use at farm level in Less Developed Countries, with particular reference to smallholding agriculture in the Colombian Andean region. The comparison of the indicators with regard to the total environmental risk suggests that simple indicators not relying on an exposure-toxicity ratio approach cannot be used as reliable proxies for more complex ones, i.e. indicators based on an exposure-toxicity ratio approach. The choice of the indicator to be used for a single environmental compartment is likely to depend on specific research, management or policy needs, on the availability of data and other necessary resources, and on an accurate analysis of the characteristics of the various indicators. ETR indicators, such as EPRIP show a comparative advantage over non-ETR in best combining the need for a relatively simple tool to be used in contexts of limited data availability and resources, such as those usually characterizing Less Developed Countries, and that of a reliable estimation of environmental risk. Indicators not based on an exposure-toxicity ratio approach such as PestScreen remain useful and accessible tools for discriminating between different pesticides prior to application. Concerning the human health risk, simple algorithms such as the OHRI or that proposed by Dosemeci et al. (2002) seem more appropriate than complex ones in assessing human health risk in Less Developed Countries. This study also pointed out the need for further research on health risk indicators and their validation under the conditions encountered in Less Developed Countries.

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Suitability of pesticide risk indicators for Less Developed Countries: A comparison

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Supplementary data

A - Short description of the indicators

EIQ

The Environmental Impact Quotient (EIQ) (Kovach et al., 1992) estimates the environmental impact of a pesticide by aggregating the hazard posed to farm workers, consumers and the local environment in one score. Each of these three components in the equation is given equal weight, but within each component, factors are given a different weighting (1, 3 or 5) in order to represent their importance. Similarly, toxicological data, which are drawn from different sources and databases, are normalized into a three level scale depending on their danger, i.e. 1 for low, 3 for medium and 5 for high toxicity.

$$EIQ = \{C[(DT \times 5) + (DT \times P)] + [(C \times ((S + P)/2) \times SY) + L] + [(F \times R) + (D \times ((S + P)/2) \times 3) + (Z \times P \times 3) + (B \times P \times 5)]\} / 3$$

Where: DT = dermal toxicity; C = chronic toxicity; SY= systemicity; F = fish toxicity; L = leaching potential; R = surface loss potential; D = bird toxicity; S = soil half-life; Z = bee toxicity; B = beneficial arthropod toxicity; P = plant surface half-life.

An EIQ field use rating (FUR) allows the EIQ to be calculated for pest control strategies (equation 2).

$$EIQ\ (FUR) = EIQ \times (\%\ active\ ingredient) \times rate$$

PestScreen

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PestScreen was developed as a screening tool to provide a relative assessment of pesticide hazards to human health and the environment (Juraske et al., 2007). The indicator provides a ranking approach, which not only includes data on toxic effects and bioaccumulation, but also on persistence and mobility of pesticides in the environmental compartments. The indicator provides a simple categorical distinction between pesticides as a function of application dose, and three hazard categories, i.e. fate, exposure and toxicity.

$$\text{PestScore} = D^* \left[\left(\sum F_{i=2} / 2\right) + E_{i=1} + \left(\sum T_{i=4} / 4\right)\right]$$

Where: D = application dose; $\sum F_{i=2}$ is the sum of overall persistence and long-range transport potential; E is the intake fraction; $\sum T_{i=4}$ is the sum of toxicity for rats, bees, fish and humans.

Each hazard category is given the same weight, and is scored on a 1 to 4 scale, i.e, low to very high concern. The hazard category's sub-scores are calculated using physical and chemical properties and cut-off criteria.

POCER

The pesticide occupational and environmental risk indicator (POCER) was developed by Vercruysse and Steurbaut (2002). It consists of ten modules covering both human health and environmental risk, which are based on the modules of Directive 91/414/EC (CEC, 1994) for the evaluation and acceptance of plant protection products in the European Union. A risk index is calculated for each module as the quotient of the estimated human exposure of the predicted environmental concentration and a toxicological reference value. The latter are endpoints defined by the Annex VI of the Directive 91/414/EC (CEC, 1994). For example, the risk index for the worker is calculated as

$$RI_{worker} = DE \times Ab_{DE} / AOEL$$

Where DE is the dermal exposure (mg/person/day), Ab_{DE} is the dermal absorption factor (fraction), and the AOEL is the Acceptable Operator Exposure Limit (mg/kg body weight/day).

The ten risk indices are aggregated into a total risk indicator by transforming each index into a value ranging from 0 to 1. In order to do that, a lower and an upper limit have to be established for the ten risk indices. The risk of a pesticide to the different components depends on the extent to which the lower limit is exceeded. Finally, the total risk of a pesticide is calculated by summing the values of the ten components (i.e. assuming equal weight).

EPRIP

The Environmental Potential Risk Indicator for Pesticide (EPRIP) was first developed by Padovani et al. (2004) and then updated by Trevisan et al. (2009) to improve the indicator,

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and in particular its applicability to different weather conditions. EPRIP is based on an ETR approach, by using the predicted environmental concentration estimated at local scale divided by short-term toxicological parameters (i.e. LD_{50}, NOEL). The ETR values are then normalized into risk points (RP) using a scale ranging from 1 to 5, where 1 represents no risk and 5 represents very large risk. Finally, to obtain the overall EPRIP score, the RP values for the different compartments are multiplied as follows:

$$EPRIP = RP_{gw} \times RP_{sw} \times RP_{s} \times RP_{a} + 25 \times N4 + 50 \times N5$$

Where RP_{gw} is the risk point for groundwater, RP_{sw} is the highest risk point among six different values for surface water, RP_{s} is the risk point for soil, RP_{a} is the risk point for air, N4 is the number of RP values equal to 4 and N5 is the number of RP values equal to 5.

PIRI

The Pesticide Impact Rating Index (PIRI) (Kookana et al., 2005) assesses the off-site migration potential of pesticides and risk of surface and groundwater contamination. PIRI makes use of an exposure-toxicity ratio approach and is based on an ad hoc developed software package. The risk assessment is based on pesticide use; the pathway through which the pesticides are released to the water resources (drift, runoff, erosion, leaching) and the value of the water resources threatened. Each component is quantified using pesticide characteristics (e.g. toxicity to organisms at different trophic levels, i.e. fish, daphnia, algae), environmental and site conditions (e.g. organic carbon content of soil, water input, slope of land, soil loss, recharge rate, depth of water table).

OHRI

The Operator Health Risk Indicator (OHRI) (Bergkvist, 2004) provides a measure of risk to the pesticide operator. It combines data on hazard and exposure and combines them with data on intensity of pesticide use. The toxicity values were drawn from the EU risk phrases defined in Annex II of the EU Directive 67/548/EEC as amended by the EU Directive 2001/59/EC and scored by the authors. The protective factors of different pieces of personal protective equipment, used to calculate the indicator's value, are drawn mainly from the UKPOEM (1992).

$$OHRI = AT \times OT \times FT \times AMO \times PMO$$

Where: AT = area treated; OT = operator toxicity; FT = formulation type; AMO = application method; PMO = use of personal protective equipment.

Dosemeci et al. (2002)

Dosemeci et al. (2002) developed a quantitative method for estimating the intensity of exposure to pesticides in the agricultural sector. The algorithms developed, i.e. a detailed and a general one, consider different factors which contribute to the exposure of the operator to

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pesticides. The exposure scores assigned to each factor are mainly derived from empirical studies in the scientific literature.

$$\text{Intensity level} = [(\mathit{Mix} \times \mathit{Enclosed}) + (\mathit{Appl} \times \mathit{Cab}) + \mathit{Repair} + \mathit{Wash}] \times \mathit{PPE} \times \mathit{Repl} \times \mathit{Hyg} \times \mathit{Spill}$$

Where: *Mix* is a score for the method of pesticide mixing; *Enclosed* is a score for whether or not an enclosed mixing system is used; *Appl* is a score related to the application method; *Cab* refers to whether or not a tractor with enclosed cab and/or charcoal filter is used; Repair is a score for the status of maintenance of the equipment; *Wash* is a score for the practice of washing the equipment after pesticide application; *Repl* is a score for the rate of replacement of old protective gloves; *Hyg* is a score for the practices of personal hygiene; *Spill* is a score for whether or not clothes are changed after a spill.

B- Overview of data requirements

Table 7. Data used to calculate the indicators

Data	Indicators*						
	EIQ	Pest Screen	POCER	EPRIP	PIRI	OHRI	Dosemeci et al. (2002)
PESTICIDE APPLICATION							
Application method			*			*	*
Application rate	*	*	*	*	*		
Duration of re-entry			*				
Exposure area for bystanders			*				
Frequency of application	*	*	*	*	*		
Inhalation exposure for the applicator			*				
Minimum number of days from application of pesticides to first rainfall/irrigation					*		
Parcel area			*	*	*	*	
Parcel perimeter				*			
Safety practices (washing, changing clothes, etc.)							*
Use of personal protective equipment			*			*	*
Transfer factor for re-entry			*				
Width of buffer zone					*		
Work rate (ha/h)			*				
PESTICIDE PROPERTIES							
Henry constant				*			
k_{oc}				*	*		
Long range transport potential		*					
Mode of action	*						
Molecular weight				*			
Overall persistence		*					
Pesticide composition (active ingredients)	*	*	*	*	*		
Pesticide formulation (liquid/powder)			*			*	
Pesticide half-life in soil	*		*	*	*		
Pesticide solubility in water				*			
Plant surface residue half-life	*						
Vapour pressure				*			
TOXICITY							
Acceptable daily intake (ADI)		*					
Acceptable operator exposure limit (AOEL)			*				
EC_{50} algae			*	*	*		
EC_{50} daphnia			*	*	*		
LC_{50} earthworms			*	*			
LC_{50} fish	*	*	*	*	*		
LC_{50} rabbit/rat	*						
LD_{50} bees		*	*				
LD_{50} birds			*				
LD_{50} rat		*		*			
Long-term health effects	*						
Operator toxicity						*	
Toxicity to bees	*						
Toxicity to beneficial arthropods	*		*				
Toxicity to birds	*						

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Table 7 (continued). Data used to calculate the indicators

Data	Indicators*						
	EIQ	PestScreen	POCER	EPRIP	PIRI	OHRI	Dosemeci et al. (2002)
SOIL							
Bulk density of soil			*	*			
Estimated average soil loss during period of interest					*		
Slope of land to water body				*	*		
Soil depth			*				
Soil moisture					*		
Soil organic carbon content				*	*		
Soil type				*	*		
WATER BODIES							
Annual recharge rate				*			
Depth of nearest water body			*	*			
Depth of water table				*	*		
Diameter of nearest water body					*		
Distance from edge of crop to water body				*	*		
Groundwater and runoff potential	*						
Recharge rate during period of interest					*		
Water table thickness				*			
Width of nearest water body			*	*			
METEOROLOGICAL CONDITIONS							
Average maximum air temperature during period of interest					*		
Maximum daily rain				*			
Mean annual precipitation				*			
Mean annual temperature				*			
Total rainfall during period of interest					*		
OTHER DATA							
Body weight of birds			*				
Body weight of bystanders			*				
Crop interception factor			*	*			
Daily food intake by birds			*				
Dermal absorption factor			*				
Drift			*				
Drinking water standard				*			
Intake fraction		*					
Leaf area index			*				
Total irrigation during period of interest					*		

* An asterisk indicates that the data was used in calculating the respective indicator.

The specific values used to calculate the indicators, as well as sources and assumptions made, are to be found in Rahn, E., 2010. Environmental and health risk indicators to assess pesticide use. A comparison of different indicators for the case of potato production in La Hoya, Colombia. Master thesis, Department of Geography, University of Zurich, Switzerland.

C – Criteria for the comparison based on key indicator characteristics

Table 8. Criteria for the comparison based on key indicator characteristics and corresponding scores.

	Scores Criteria	*	**	***
User friendliness	Data availability	Not available (additional assumptions needed)	Available for some pesticides	Easily available
	Calculation procedure	Calculation procedure knowledge-intensive and time-consuming	Calculation procedure either knowledge intensive or time-consuming	Calculation procedure neither knowledge intensive nor time-consuming
	Score interpretation	Relative comparison (ranking)	Risk classes given when single applications are considered	Risk classes given both when single applications and control strategy are considered
Ability to represent the specific system under study	Site specific data	No site specific data used	-	Site specific data used
	Compartments considered (environment)	One-two compartments	Three compartments	Four-Five compartments
	Compartments considered (health)	One compartment	Two compartments	Three compartments

D - Additional tables

Table 9. Correlation between rankings of the 581 pesticide applications for risk to soil (Spearman correlation test)

	EPRIP	POCER	Application rate
EPRIP	1.00		
POCER	0.82 **	1.00	
Application rate	0.07	0.42 **	1.00

* p > 0.05; ** p > 0.01

Table 10. Correlation between rankings of the 72 control strategies for risk to soil (Spearman correlation test)

	EPRIP	POCER	Application rate
EPRIP	1.00		
POCER	0.38 **	1.00	
Application rate	0.14	0.32 **	1.00

* p > 0.05; ** p > 0.01

Table 11. Correlation between rankings of the 581 pesticide applications for risk to beneficial arthropods (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	-0.50 **	1.00	
Application rate	0.98 **	-	1.00

* p > 0.05; ** p > 0.01

Table 12. Correlation between rankings of the 72 control strategies for risk to beneficial arthropods (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1,00		
POCER	0,09	1,00	
Application rate	0,99 **	0,09	1,00

* p > 0.05; ** p > 0.01

Table 13. Correlation between rankings of the 581 pesticide applications for risk to birds (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.43 **	1.00	
Application rate	0.94 **	0.25 **	1.00

* p > 0.05; ** p > 0.01

Table 14. Correlation between rankings of the 72 control strategies for risk to birds (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.35 **	1.00	
Application rate	0.96 **	0.28 *	1.00

* p > 0.05; ** p > 0.01

Table 15. Correlation between rankings of the 581 pesticide applications for risk to bees (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.05	1.00	
Application rate	0.96 **	0.90 *	1.00

* p > 0.05; ** p > 0.01

Table 16. Correlation between rankings of the 72 control strategies for risk to bees (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.43 **	1.00	
Application rate	0.97 **	0.34 **	1.00

* p > 0.05; ** p > 0.01

Table 17. Correlation between rankings of the 581 pesticide applications for risk to farm worker (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.56 **	1.00	
Application rate	0.91 **	0.51 **	1.00

* p > 0.05; ** p > 0.01

Table 18. Correlation between rankings of the 72 control strategies for risk to farm worker (Spearman correlation test)

	EIQ	POCER	Application rate
EIQ	1.00		
POCER	0.49 **	1.00	
Application rate	0.97 **	0.46 **	1.00

* p > 0.05; ** p > 0.01

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